Fundamental P

*Fundamental Physics at NASA/JPL: Status and Plans**

Ulf Israelsson, Jet Propulsion Laboratory, California Institute of Technology

- Research carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA

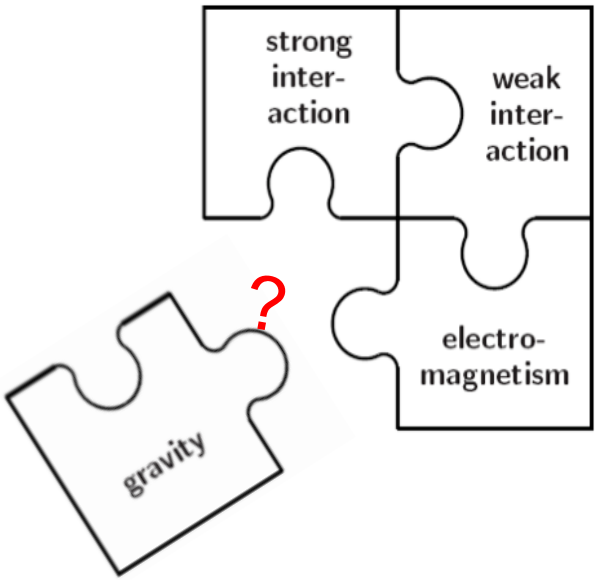
Agenda

- ***Introduction and Context***
- ***On-going ISS experiments***
- ***Cold Atom Laboratory***
- ***BECCAL & Future Experiments under study***
- ***Summary***

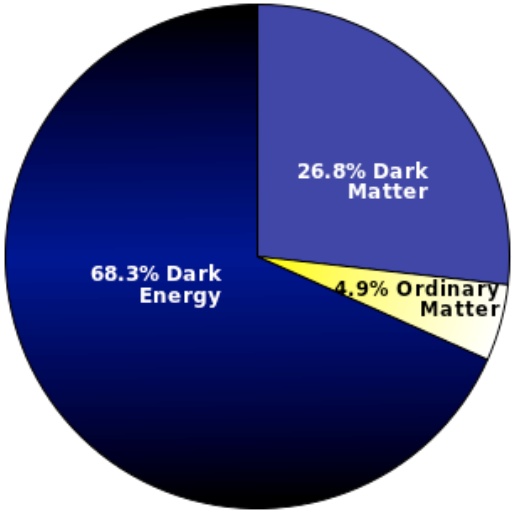
Fundamental Physics

Context: Physics in the 21st Century

- **Physics is standing at the threshold of major discovery**
  - Our two foundational descriptions of nature, quantum mechanics and general relativity, are incompatible with each other.
  - When this conflict is resolved, a different view of reality may emerge that unifies matter, space, and time.
  - LIGO's has directly observed gravitational waves.
  - CMB experiments search for quantum-gravity unification at Planck scale.



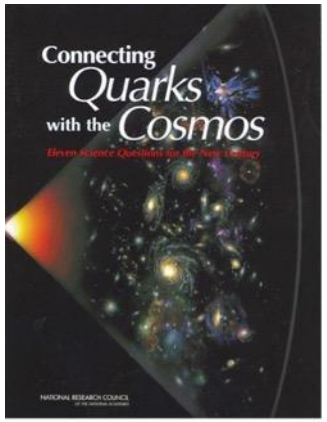
- **Cosmological observations indicate that our understanding is in need of drastic modification.**



Fundamental Physics

Today's important physics questions

Quarks to Cosmos - 11 questions for the new century



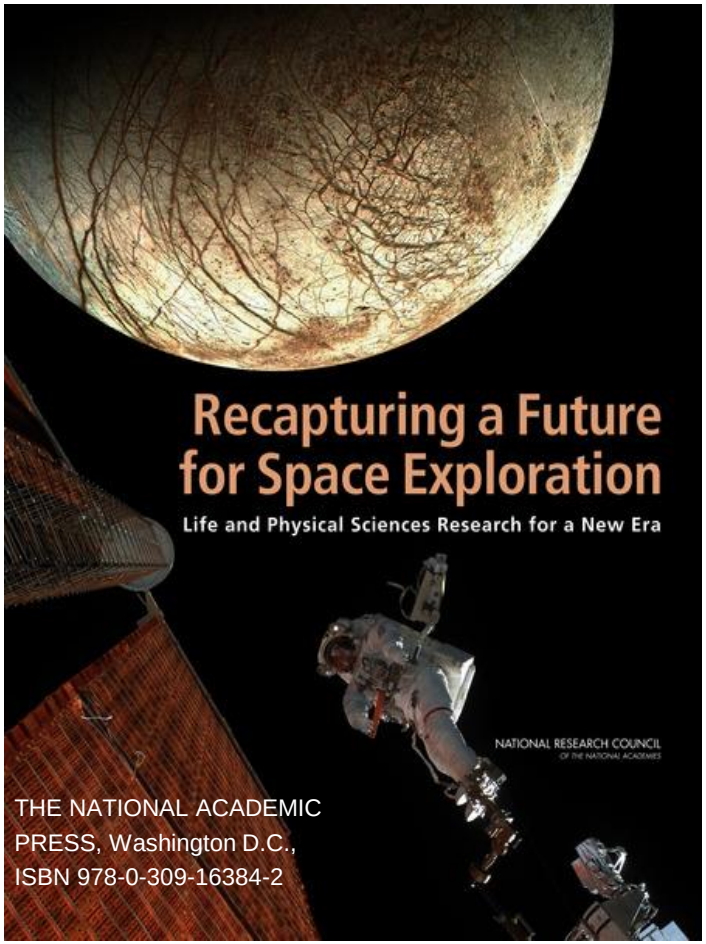
- **What is the dark matter?**
- **What is the nature of the dark energy?**
- **How did the Universe begin?**
- **Did Einstein have the last word on gravity?**
- **What are the masses of neutrinos and how have they shaped the evolution of the Universe?**
- **How do cosmic accelerators work and what are they accelerating?**
- **Are protons unstable?**
- **Are there new states of matter at exceedingly high density and temperature?**
- **Are there additional space time dimensions?**
- **How were the elements from iron to uranium made?**
- **Is a new theory of matter and light needed at the highest energies?**

NSF
NIST
DOE
NASA SMD
NASA HEOMD

Fundamental Physics

NRC 2011 FP Decadal Recommendations

- **FP1:** Research on Complex Fluids and Soft Matter
  - PK-4 [ESA/NASA/NSF]
- **FP2:** Research to Understand Nature's Fundamental Forces and Symmetries
  - ACES (ESA) SOC & QWEP (ESA studies)
  - Microscope (CNES); QTEST (NASA Study)
  - Dark Energy & Dark Matter experiments
  - BECCAL (DLR/NASA)
- **FP3:** Research Related to the Physics and Applications of Quantum Gases
  - Cold Atom Laboratory
  - BECCAL (DLR/NASA)
- **FP4:** Investigations of Matter Near Critical Points
  - DECLIC-ALI-R [CNES]



Fundamental Physics

Fundamental Physics Program Roadmap

PK4 (ESA/NASA) → ACES (ESA/NASA) → CAL → BECCAL (DLR/NASA) → Free Flyer

2016-2019 2018 – 2020 2018-2021 2021-2024 2024+

Unique Space Environment

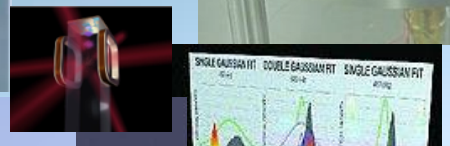
- Microgravity
- Low vibration
- Large spatial extent
- Large gravitational field variation
- Free from atmospheric interferences
- Inertial frame

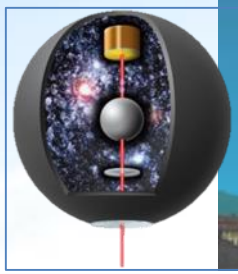
Fundamental Science

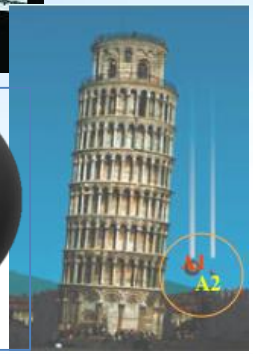
- Study of quantum systems
- Testing equivalence principle
- Testing variation of fundamental constants
- Testing Einstein relativity theories
- Testing fundamental symmetries
- Understanding gravity and laws of nature
- Probe dark energy and dark matter

Technology

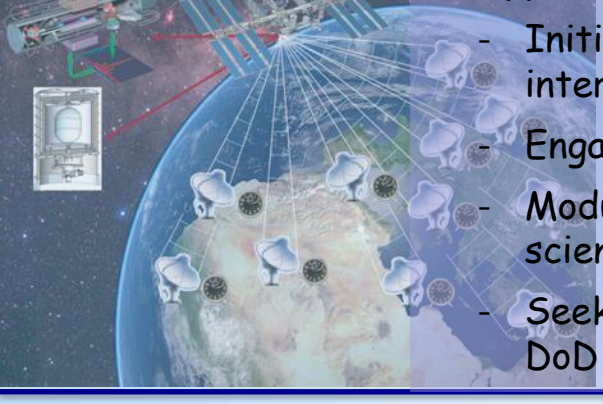
- Ultra-stable clocks
- Ultra-stabilized lasers and optical frequency combs
- Precision time transfer and ranging
- Atom interferometer inertial sensors
- BEC and quantum degenerate gas







ACES → CAL– BECCAL



Approach

- Initial low cost effort through international collaborations
- Engaging science and research community
- Modular capability and hardware build-up from science engagement, to instruments, to missions
- Seek multi-agency collaborations with NIST, DoD and DOE

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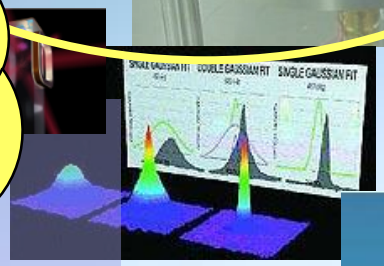
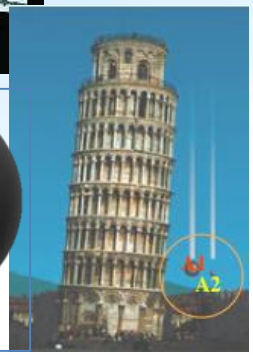
Research in atomic physics and precision measurements leads to new tools and capabilities for Fundamental Physics Discovery





ACES → CAL– BECCAL

Approach

- Initial low … international
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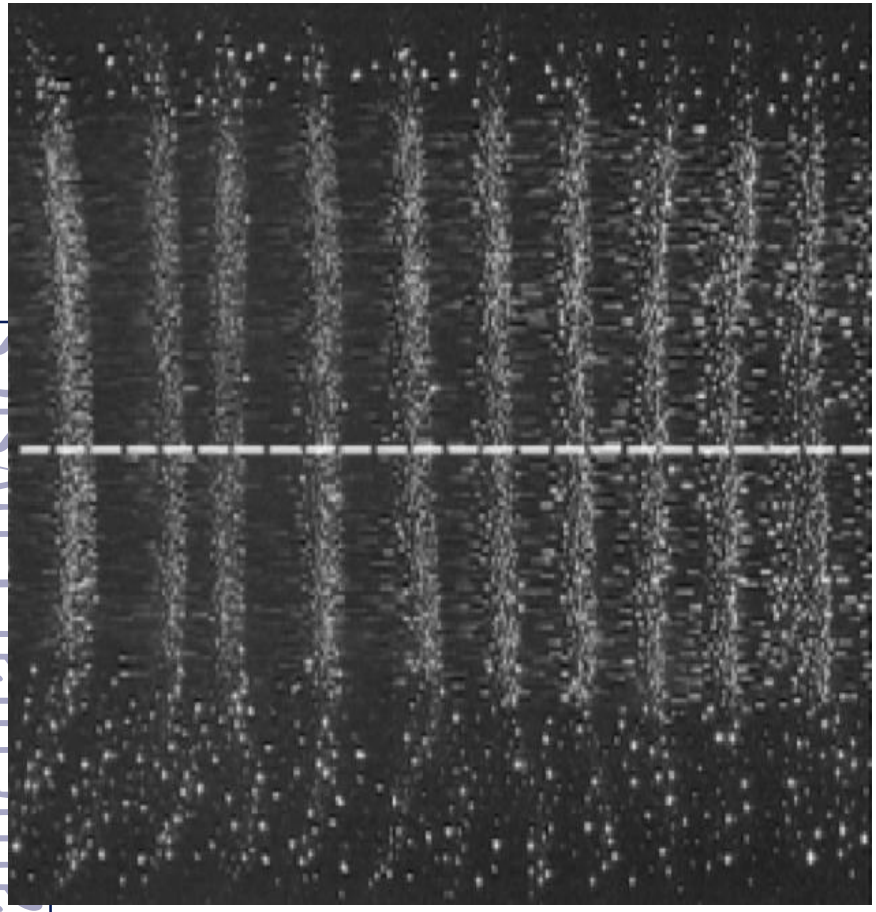
ESA PK-4: Non-linear Wave Phenomena

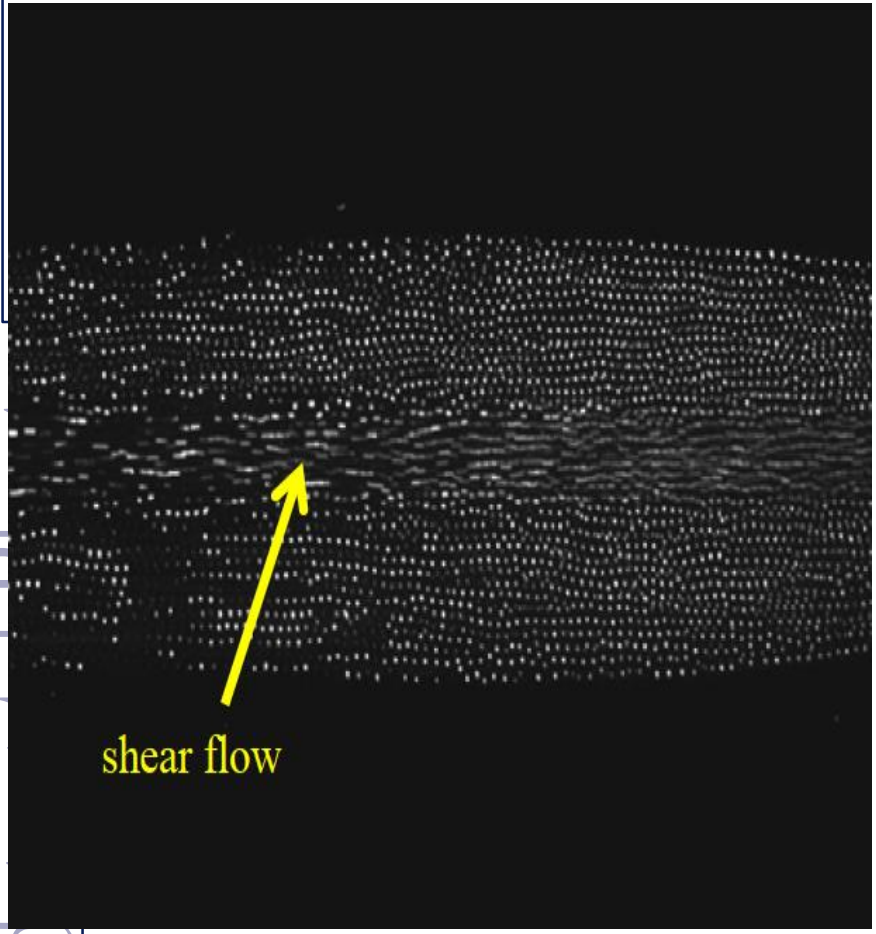


Can we extend the physical understanding of non-linear dust acoustic wave phenomena by modulating the ion density?

A team of scientists will investigate the physics of wave synchronization using dusty plasma. Dust plasmas are suitable for the study because they meet essential requirements, self-excited, nonlinearity, ease of modulation, diagnostics for wave motion.

PI: J. Goree (Univ. of Iowa)
Co-I: B. Liu (Univ. of Iowa)
Co-I: G. Ganguli (NRL)
Co-I: A. Melzer (Univ. Grefswald)

ESA PK-4: Condensed Matter Analog



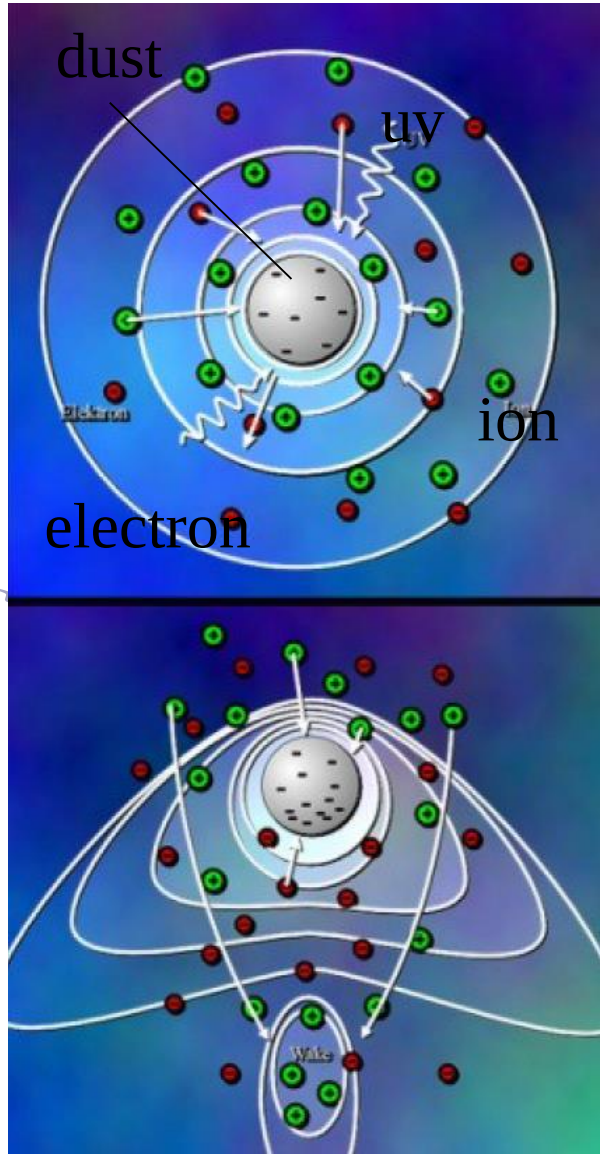
Can we exploit unique properties of dusty plasma to verify the theoretical prediction of viscous heating?

Does a 3D dusty plasma exhibits stick-slip motion during plastic deformation induced by laser shear force?

A team of scientists will investigate he physics of liquids and fluids, soft condensed matter, and non-equilibrium statistical mechanics.

PI: B. Liu(Univ. of Iowa)
Co-I: J. Goree (Univ. of Iowa)

ESA PK-4: Charging, Interactions, Kinetics



Can we determine charges on the dust more accurately?

What is the role of directed ions currents on the particle interaction?

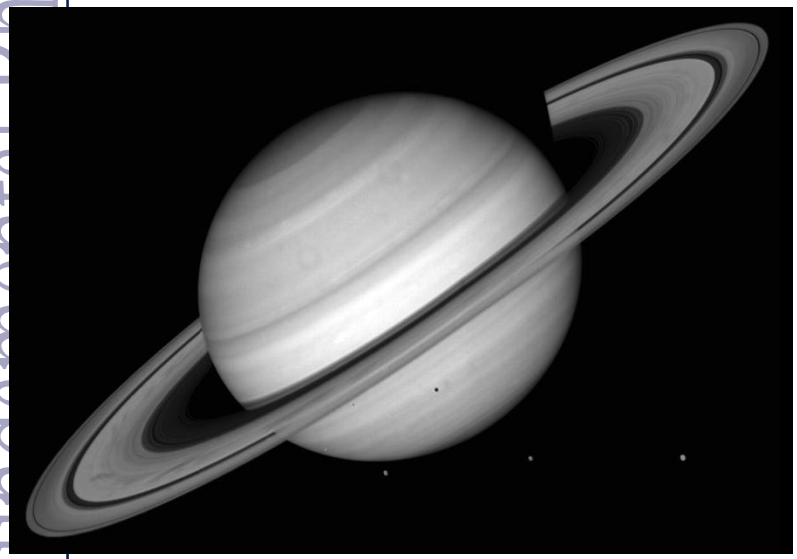
Can we use the dusty plasma to understand a diverse range of physical phenomena, including fluid mechanics, wave properties at the kinetic level

A team of scientists will use PK-4 apparatus to understand the charging, interactions of micro-particles, and kinetics

PI:U. Konopka (Auburn Univ.), Co-I: E. Thomas (Auburn Univ.), Co-I:J. Williams (Wittenberg Univ.)

Fundamental Physics

ESA PK-4: Ice-Grain complex plasma



Can we understand noctilucent clouds, Saturn's diffuse rings, which are composed in whole or in part of water-ice dust plasmas?

Why are the water-ice grains in low ambient pressures needle-shaped rather than spherical?

Why do the needle-shaped water-ice grains mutually co-align?

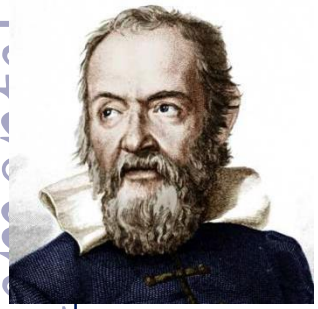
Why do the ice grains move in well-defined vortices?

A team of scientists is investigating the physics of ice-grain formation in plasmas by developing techniques applicable to PK-4 mission.

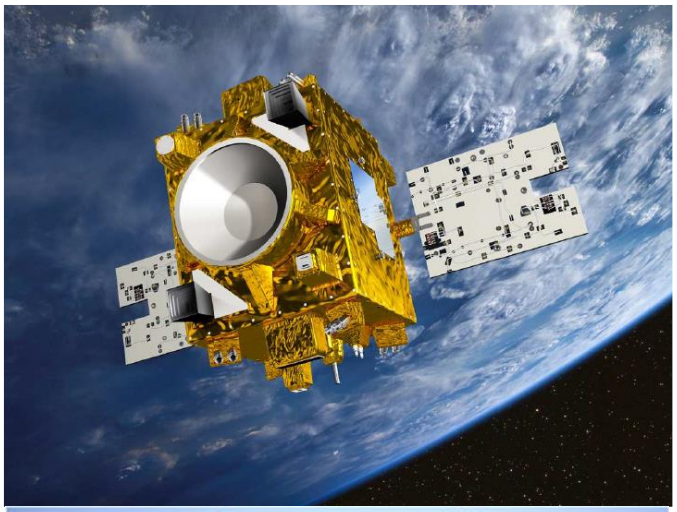
PI: P. Bellan (Caltech)

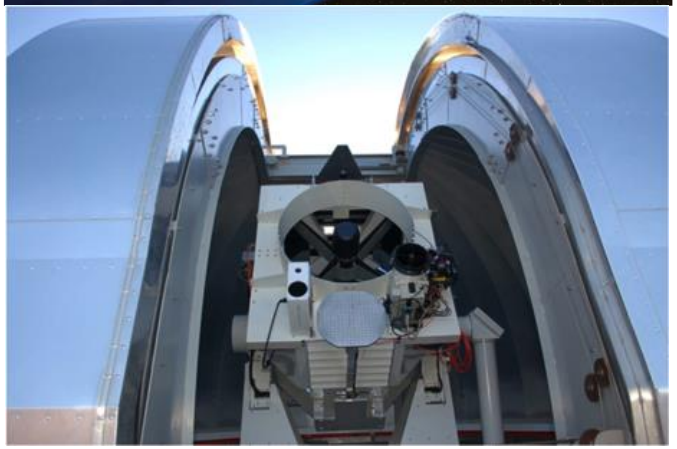
CNES MICROSCOPE: Test of Einstein

Galileo on ground



MICROSCOPE in space





JPL TMO

Is Einstein's equivalence principle valid to one part in 10^{15} or beyond?

A team of scientists will enhance the test precisions by determining the orbit of the satellite using the state-of-the-art laser ranging technique.

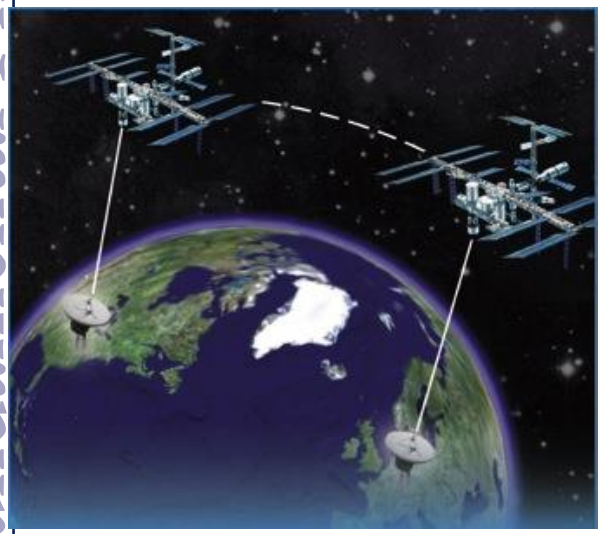
PI: S. Turyshev (JPL)

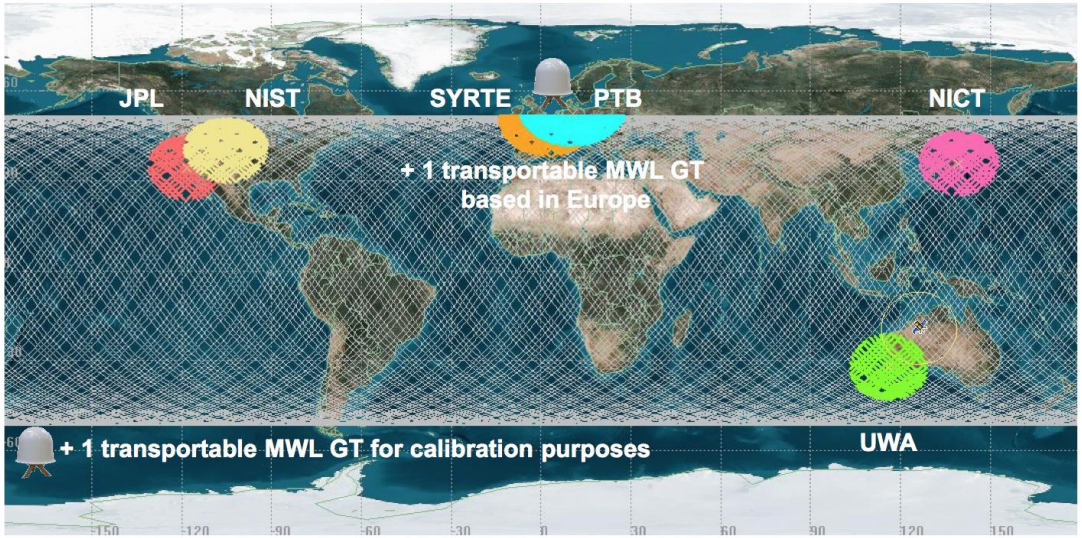
ESA ACES Mission: US participation

Atomic Clock Ensemble in Space (ACES) – an ESA ISS Experiment (2019 Launch)

US Participation: ESA deliver two ground stations in US (JPL and NIST) for the overall ACES global clock comparison network.

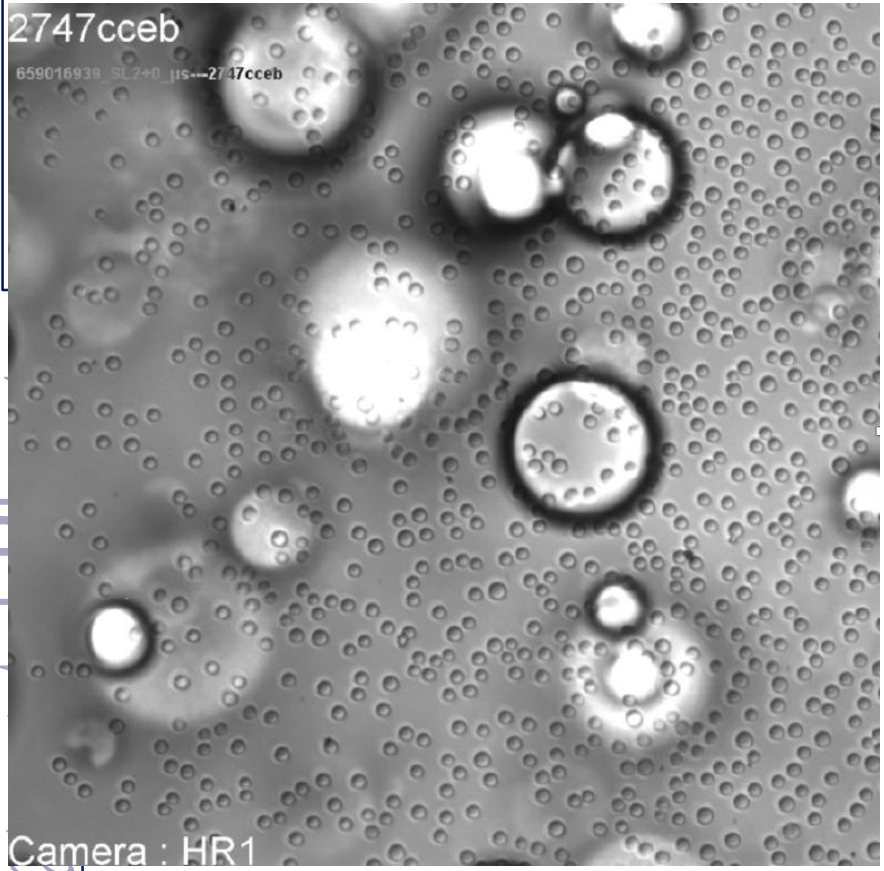
- **Demonstrate and validate a new generation of cold atom clocks in space**
- **Demonstrate the capability to compare ground clocks on a world-wide basis at high state of the art precisions.**
- **Test fundamental laws of physics to high accuracy (gravitational Red-shift, change of fine structure constant, and anisotropy of light.)**
- **Detect possible dark energy signatures**





Fundamental Physics

CNES DECLIC ALI-R : Scaling, Universality, and RG



Is the scaling hypothesis ultimately valid near the critical point?

Are the Nobel prize winning RG (Renormalization Theory) predictions still valid near extremely close to the critical point?

Are the current classical-to-critical crossover theories valid in the simple fluid systems?

DECLIC ALI-R will make the most precise measurements of light attenuation property of a simple fluid near its liquid-gas critical point, which is not possible on the ground.

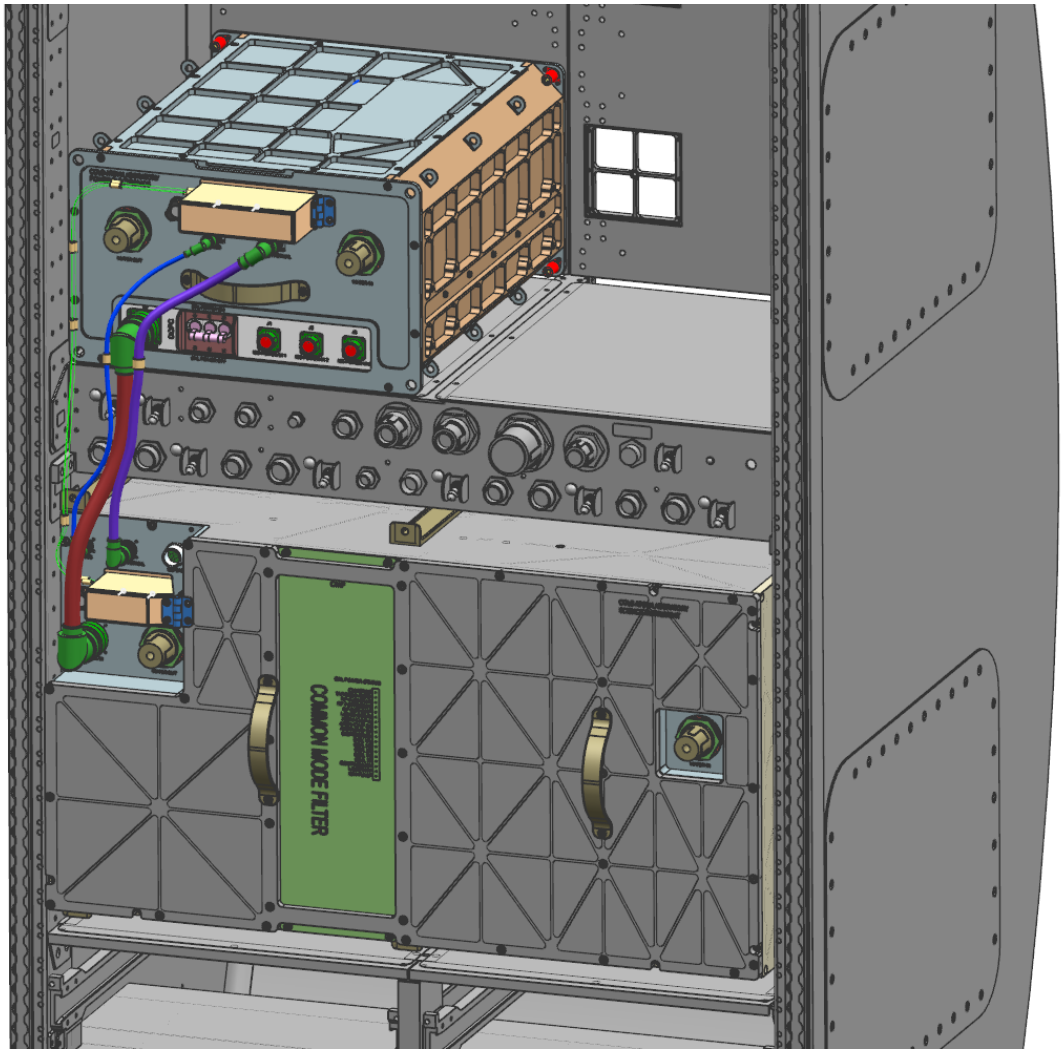
U.S. PI: I. Hahn (JPL, US), CNES PI: Y. Garrabos (Univ. Bordeaux, France)

NASA Cold Atom Laboratory Configuration

Power Electronics
& Rack infrastructure
(5th Locker)

Science Instrument
(Quad Locker)

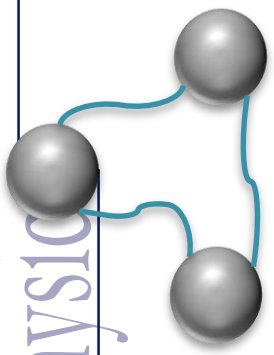
- Science Module
- Science support functions
- Rack infrastructure



Fundamental Physics

CAL science: Studies of few-body physics in microgravity

Searching for universal features in the behavior of quantum collisions between a few particles might shed light into how complexity can arise from simple underlying physics



CAL will make precise measurements of so-called Efimov States and explore their universality, yielding new insights into how complexity can emerge from simple underlying physics

Requirements: Species: K39; 20 weeks on orbit

Eric Cornell, JILA

Peter Engels. WSU

Co-I Debbie Jin, JILA

In Memoriam, 1968-2016

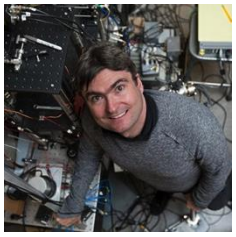
Fundamental Physics

CAL science: Testing Einstein

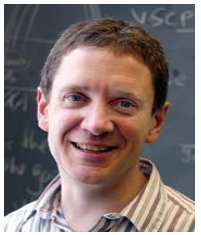
Will a potassium atom and a rubidium atom fall at precisely the same rate? Once upgraded with AI capability CAL will perform a quantum test of Einstein's Equivalence principle

This team will also demonstrate a space based atom laser, a source of coherent matter waves, using the CAL-1 science module

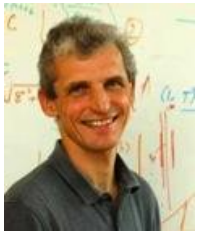
Requirements: Rb-87 for non-AI experiment (Rb +K needed for AI) 15 weeks on orbit for non-AI Experiments



CO-I H. Mueller,
UC Berkeley



Co PI N. Bigelow
U. Rochester



Co PI W. Ketterle
MIT

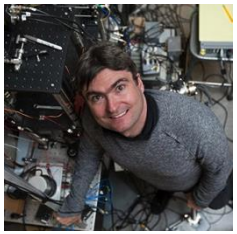
Co-I Bill Phillips
JQI

Fundament

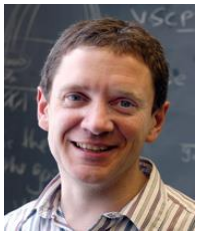
CAL Science: Testing Theories of dark Energy

This team is also interested in searching for a proposed dark energy candidate known as a chameleon field

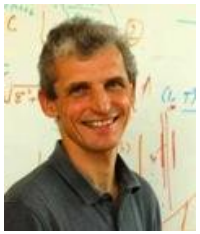
This field can potentially be observed by searching for position dependent forces in the vicinity of a surface, and would be ideal to perform on an AI enabled upgrade to CAL



CO-I H. Mueller, UC Berkeley



Co PI N. Bigelow U. Rochester

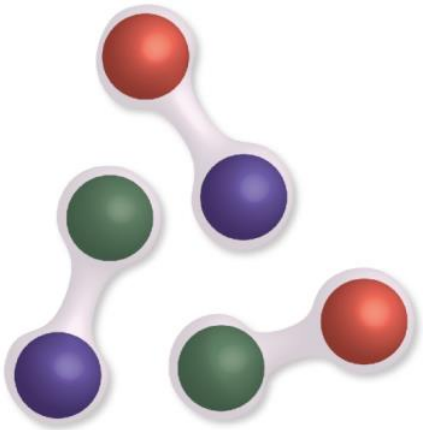


Co PI W. Ketterle MIT

Co-I Bill Phillips JQI

Fundamental Physics

CAL Science: Quantum Halo Molecules



Quantum Halo molecules are the most weakly bound of any diatomic molecules, and have the largest spatial extent. Their size in facts extends far beyond the range of the classical potential of the atoms

CAL will study the formation of these novel molecules in a new temperature regime and explore their utility for future space based tests of Einstein's equivalence principle

PI also has experiments which require AI

Requirements: Rb-87 and K-41 4 weeks on orbit for non AI experiments

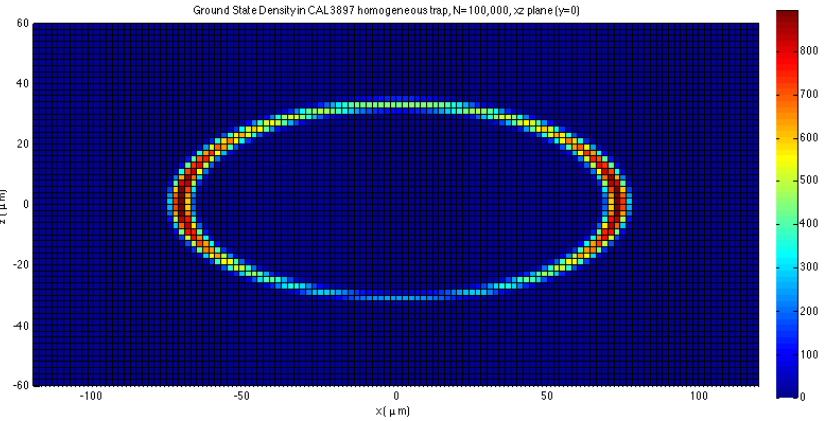
PI Jason Williams, JPL

CAL Science: Quantum bubbles

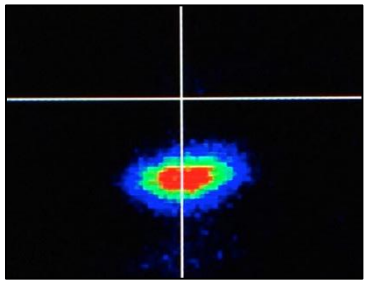
Microgravity allows us to study “bubble” quantum states that can’t be observed on earth

CAL will demonstrate this novel topology and explore features such as excitation spectra and interference effects

Requires: Species Rb-87; 12 weeks of CAL on-orbit time



On orbit bubble shaped topologies can be demonstrated for the first time



On ground atoms fall to bottom of potential

PI N. Lundblad
Bates College

Co-I Dave Aveline
JPL

CAL Science: Studies of Adiabatic expansion

CAL will test novel techniques to employ adiabatic expansion to achieve extremely low temperatures in microgravity

In a separate experiment this team will develop a novel cold atom rotation sensor and use it to measure ISS rotations

Requirements: Species Rb 87 and K41 or K-39; 6 weeks on orbit

Adiabatic cooling: let gas expand into very weak trap. As it expands it steadily cools, just as an aerosol can cools as you spray it

PI Cass Sackett, U. Va.

CAL - Ground based Research

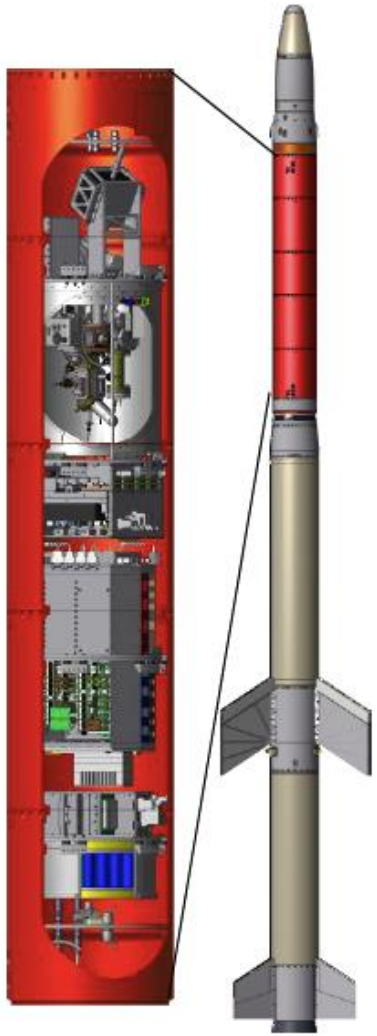
Studies of Magnon Interferometry and Cooling (Dan Stamper-Kern, UC Berkeley): A magnon is a collective excitation of the spin structure of atoms in an optical lattice. This proposal will study how they can be used to make ultra-high precision atom interferometers and to achieve extremely low-entropy states.

This experiment could be performed in an upgraded version of CAL

High Precision Microwave Spectroscopy of Long-Lived Circular-State Rydberg Atoms in Microgravity (Georg Raithel, U. Michigan) This experiment is aimed at precision measurement of fundamental constants such as the Rydberg constant in microgravity. A microgravity version of this experiment could resolve such fundamental questions as the size of the proton, currently a controversial subject in particle physics hinting at physics beyond the standard model

This experiment could be a potential follow-on to CAL

Constraints: MAIUS + CAL = BECCAL

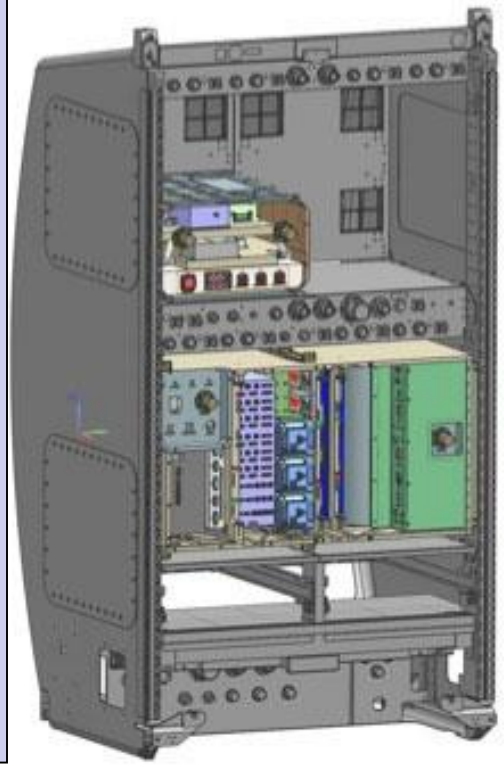


DLR
MAIUS-1
2016-2019

- 315 kg
- 300 W
- 0.55 m^3
  - 0.5 m dia
  - 2.8 m tall
- Limited access to ug

NASA
CAL-1
2017-2020

- 362 kg
- 900 W
- 0.38 m^3
  - 5/8 of Exp Rack



BECCAL

Fundamental Physics

BECCAL as CAL Follow-up mission

NASA-DLR bilateral collaborations

Provide an unique space facility for investigation opportunities

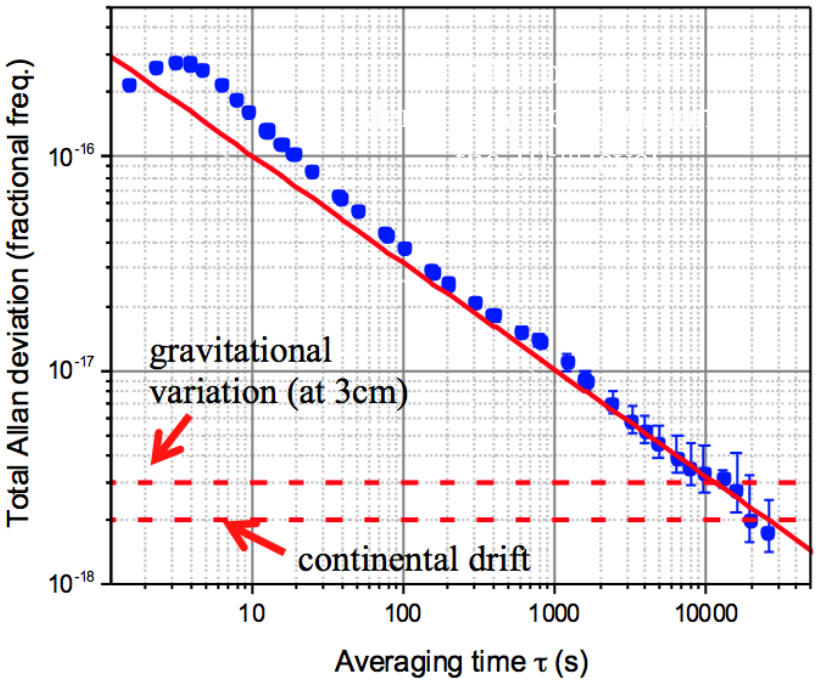
- Understanding quantum systems of atom optics, degenerate gases and their mixtures (*new and different capabilities from CAL*)
- Testing the universality of free fall (*More precise measurements than CAL*)
- Methods and phenomena for Bose-Einstein condensation, atomic mixtures, delta-kick collimation and coherent manipulation by light pulses (*Improvements over CAL*)
- Quantum phases (miscibility studies, spinor physics, etc.) in the vicinity of the transition thresholds (*Enhanced from CAL*)
- Few body and many body scaling and behaviors (*Similar to CAL*)
- Atom interferometer demonstration (*improved from CAL*)
- Satellite-based geodetic applications and Earth observation (*New from CAL*)

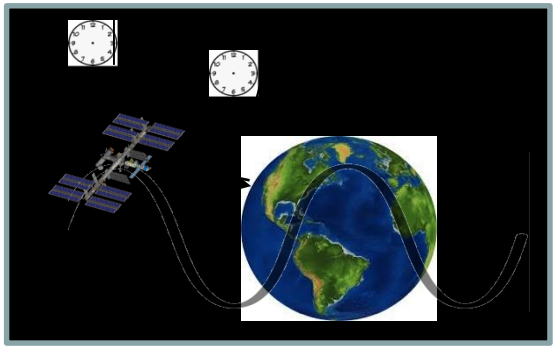
Fundamental Physics

ESA Space Optical Clock (SOC)

US participation and JPL optical clock capability development

- Tests of Einstein Theories of Gravity
  - Gravitational red-shift: light relativistic frequency shift
  - Lense-Thirring effect: Gravity frame drag effect
  - Newton's inverse square law at long distances
- Test Local Lorentz invariance
  - Isotropy of the speed of light
  - Constancy of the speed of light
  - Time dilation experiments
- Tests of Local Position Invariance
  - Universality of the gravitational red-shift
  - Time variations of fundamental constants
- Detection of Dark Matter Fields
  - Ultra-light dark matter waves, clumps, or stochastic backgrounds





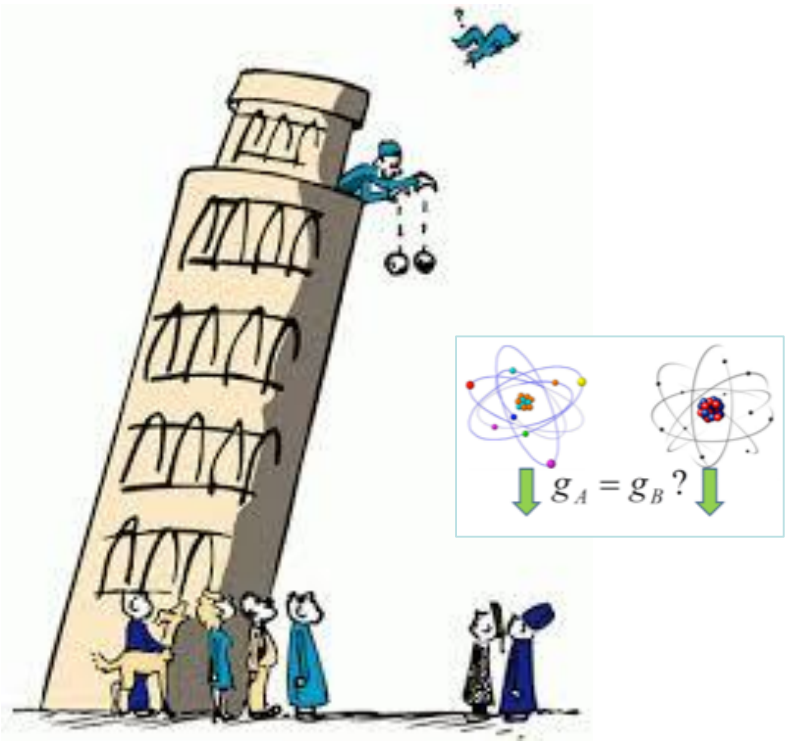
clocks for dark matter detection

Fundamental Physics

Einstein Equivalence Principle

ESA QWEP collaboration and NASA QTEST Study

- Improve the limit on violation of universality of free fall
- Look for evidence for ultra-light particles for dark matter/dark energy
- Test Space-Time dependence of quantum state
- Search for spin-gravity coupling
- Test of Quantum Electrodynamics and explore inner structure of electron at LHC energy scale and Planck Scale



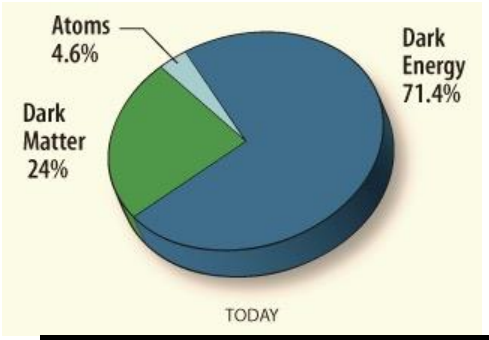
Fundamental Physics

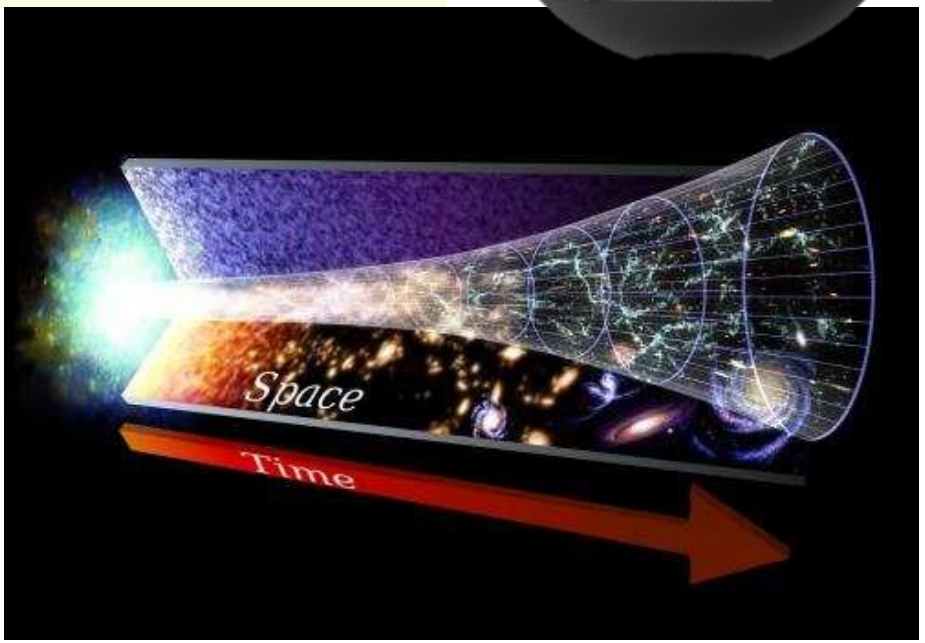
Detection of Dark Energy

Searching for Chameleon forces of dark energy fields

Seek to answer the question "What is the nature of dark energy"

- Chameleon field is one of the promising candidates for dark energy as scaler field
- Environmental screening effort must exist for a dark energy field to be consistent with all observations
- Atomic particles are not screened, providing a great opportunity for detecting Chameleon field
- ISS experiment or on another space platform can detect the dark energy field if exists or rule it out gaining valuable understanding



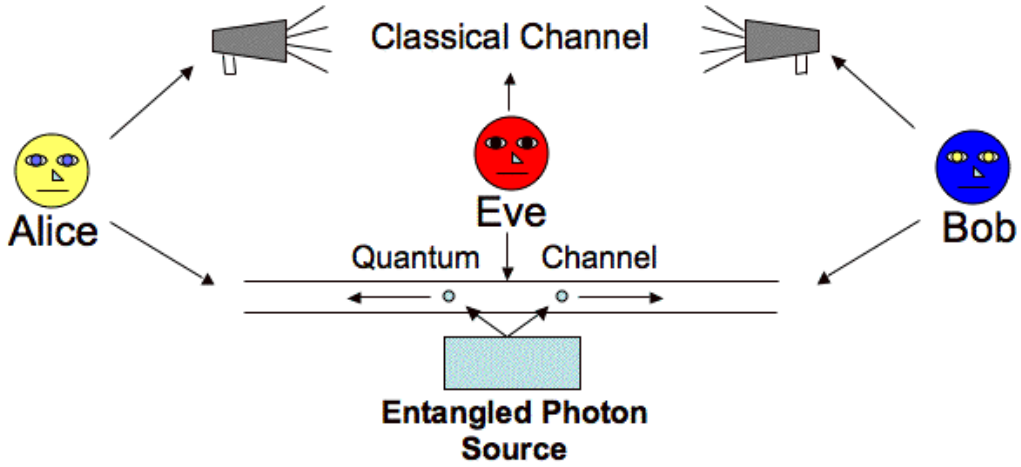


Fundamental Physics

Quantum Communications in Space

Entangled photon source and quantum network

- Ultimate communication security through quantum key distributions
- Quantum-limited reception and detections for communication efficiency and sensor precision
- Quantum system behavior in large gravity variation environment



Fundamental Physics

Summary

- **Importance of International collaborations**
- **Eagerly awaiting results from CAL**
- **Planning for CAL follow-on with BECCAL DLR collaboration**
- **Beyond ISS era**

Fundamental Physics